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Breaking Waves at an Inversion

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ABSTRACT—A sequence of photographs shows waves breaking at an inversion. Partial mixing with air above the cloud layer as breaking occurs increases buoyancy so that the air, while remaining cloudy, does not return to its original level. This behavior could be of importance in ice crystal multiplication processes.

A temperature inversion in the atmosphere or a thermocline in the ocean gives a layer that suppresses the transfer by forced or convective turbulence of heat, momentum, minor constituents such as pollution products, water vapor, or salt. Upward convection caused by solar heating of a moist land surface may lead to heat and water vapor being mixed throughout a layer capped by an inversion; downward convection in a warm lake cooled at its surface will extend downward until it reaches water of the same temperature at the thermocline.

Gravity waves travel at these interfaces with a velocity and amplitude that depend on the detail of the vertical profile of temperature and horizontal velocity; the velocity also depends on wavelength, longer waves traveling more quickly as in the case of surface gravity waves in the ocean. A familiar characteristic of water waves is that they break on reaching shallow water, as their velocity decreases. The crests tend to move ahead while the disturbance at lower levels decelerates. Waves may also break when the wind speed exceeds 7 m/s to give "whitecaps." Breaking waves of this kind lead to an enhancement of the vertical diffusion processes by giving more mechanical turbulence; more moisture and heat is transferred in the atmosphere immediately above the ocean and more heat and salinity transferred in the ocean when appropriate differences exist. In a somewhat analogous manner, waves on inversions or thermoclines may break, leading to a large local increase in mechanical turbulence and transport of air or water having different properties. Several recent studies (Ludlam 1967, Woods 1968) have shown that internal waves in the atmosphere and ocean become unstable and break as the local Richardson number (Ri) defined by

$$\mathrm{Ri}=\frac{g\beta}{(du/dz)^2}$$

becomes less than about +0.25, larger values giving stable propagating waves. (The term β is static stability in the atmosphere, for a dry or cloudy process, as appropriate, g is acceleration of gravity, and du/dz is vertical shear of horizontal velocity.)

The sequence of photographs (fig. 1) shows waves breaking at the top of an inversion that is clearly marked by the presence of a cloud deck. Cloud drops are here serving as a tracer and fail to evaporate when carried upward into the air above the general level of the cloud top. The times given for the photographs are unfortunately only accurate to $\pm\frac{1}{4}$ min, as the photographs were taken during somewhat adverse circumstances on a steep snow slope. It can clearly be seen how cloudy air from below the inversion is carried upward and then horizontally, trapping clear air below it, to become mixed as the wave descends in the breaking phase. Three waves can be distinguished. The wave (A) on the left (west) of the sequence began with a smooth profile; the other two waves (B, C) were well into the breaking stage when first observed. The left wave rears upward to reach almost the same stage that the center wave had reached at the beginning of the sequence. Note that once the wave has broken, the downwind air above the original cloud deck remains cloudy (fig. 1–VI, waves B and C). This situation persisted for at least an additional 10 min.

The waves were photographed from east of Reno, Nev., looking to the north-northeast, with a 135-mm telephoto lens. The cloud layer covered the Petersen Range (reaching some 3000 m above sea level). The cloud top is estimated at about 3750 m; the distance is 30 $\pm$2 km. It was difficult to estimate how far the waves extended away from the viewing direction. The photographs show that they were near the edge of the cloud sheet, and their width may have been quite small. Assuming that the waves were moving at right angles to the line of sight, we can estimate the following parameters to about 10 percent accuracy:

Wave crest velocity	4 m/s	
Vertical velocity of breaking wave	1.2 m/s	Wave A, photos 1–IV and 1–V
Differential horizontal velocity between breaking wave crest and base	1.2 m/s	Wave A, photos 1–IV and 1–V
Wave amplitude	150 m	
Wavelength	650 m.	

The nearest available radiosonde was at Winnemucca, Nev., about 220 km to the northeast (fig. 2). It was in the same air mass as the camera, and the ascent was made at about the same time as the cloud observations. Both Reno and Winnemucca are at approximately 1300 m

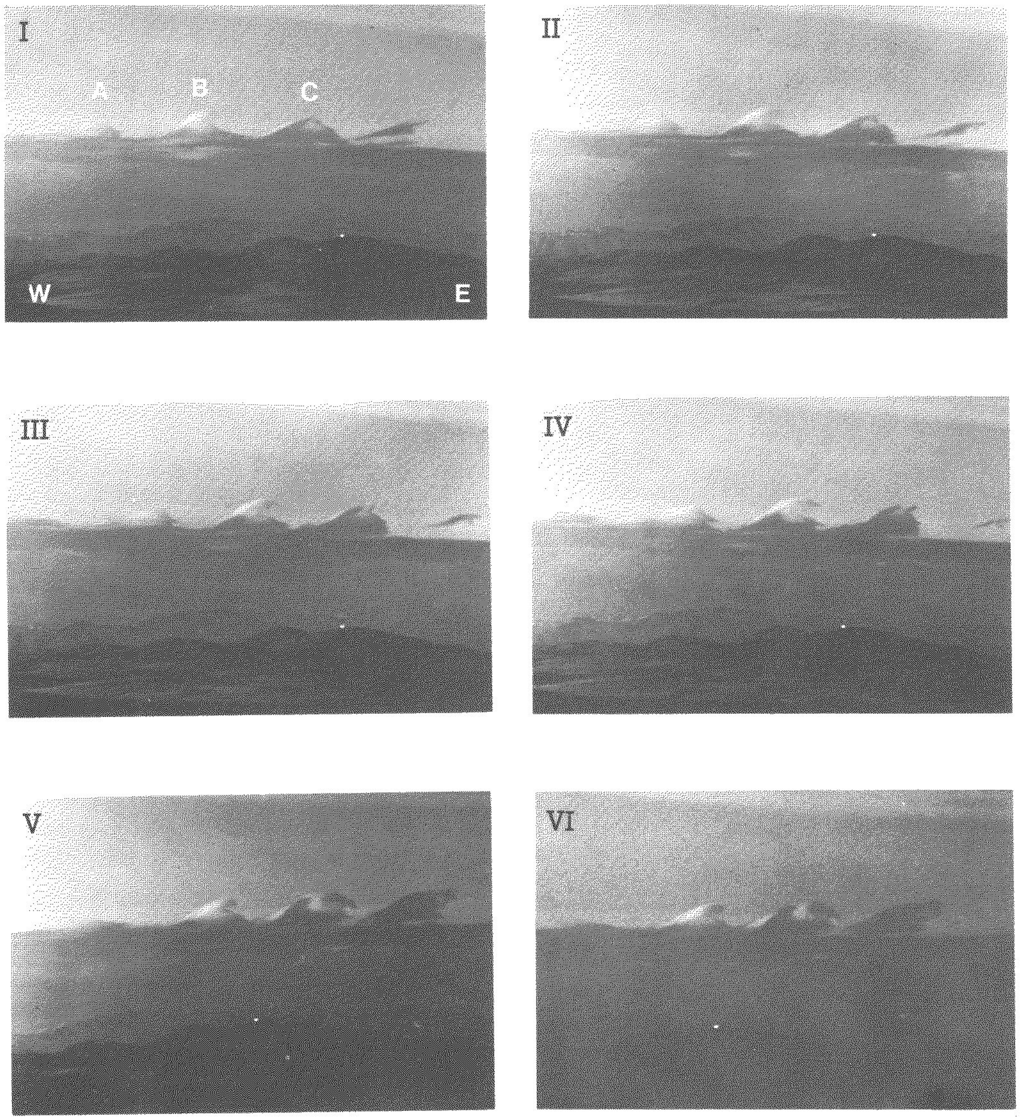

FIGURE 1.—Breaking waves over the Petersen Range, 30 km north-northeast of Reno, Nev. The time was about 1630 PST on Dec. 5, 1970. Pictures I–V are at 1-min intervals and pictures V–VI are at 2-min intervals.

above sea level. The radiosonde showed an adiabatic lapse rate up to 2500 m, an intermediate layer (not saturated) with moist adiabatic lapse rate up to 2750 m, and the inversion layer up to 2950 m. The Richardson numbers computed from this ascent are given in table 1. They suggest that the cloudy breaking waves would be possible if saturation were reached, as had occurred locally in the Reno area.

It is of interest to ask why breaking waves of this kind at inversion tops are not seen more frequently. The first possibility is that the temperature inversion is usually capped by a dry layer—as was the case at Winnemucca, Nev. Under these circumstances, the mixing on breaking would lead to a rapid evaporation of cloudy air. Radar observations show that breaking waves occur rather frequently in clear air, in association with very stable air above an inversion top giving turbulence to any passing aircraft (Atlas et al. 1970). Even here, however, it appears that wave breaking does not occur at any one place for an appreciable time—the breaking mechanism itself destroys the situation which produces it. Initiation would therefore, depend on the fortuitous arrival of an appropriate stable longer wavelength gravity wave, giving the shear necessary to cause the breaking of the shorter wavelength disturbances. Wave trains in different directions may then lead to a breaking wave of width comparable to its length as observed here. We may speculate that the waves seen here were formed in an inversion with a layer above that is somewhat more moist than usually prevails or indeed prevailed at Winnemucca. There the potential wet bulb temperature was almost constant, increasing by 0.2°C over the inversion layer, to give the cloud-air stability (Lilly 1968). Dry air mixing with the more moist overlying air would not lead to complete evaporation of the cloud drops, the breaking turbulent part of the wave falling back to a level that depended on the extent of the mixing process.

The occurrence of breaking waves of this kind is of utmost importance in the vertical mixing process. Stable progressive waves propagating at an inversion are always

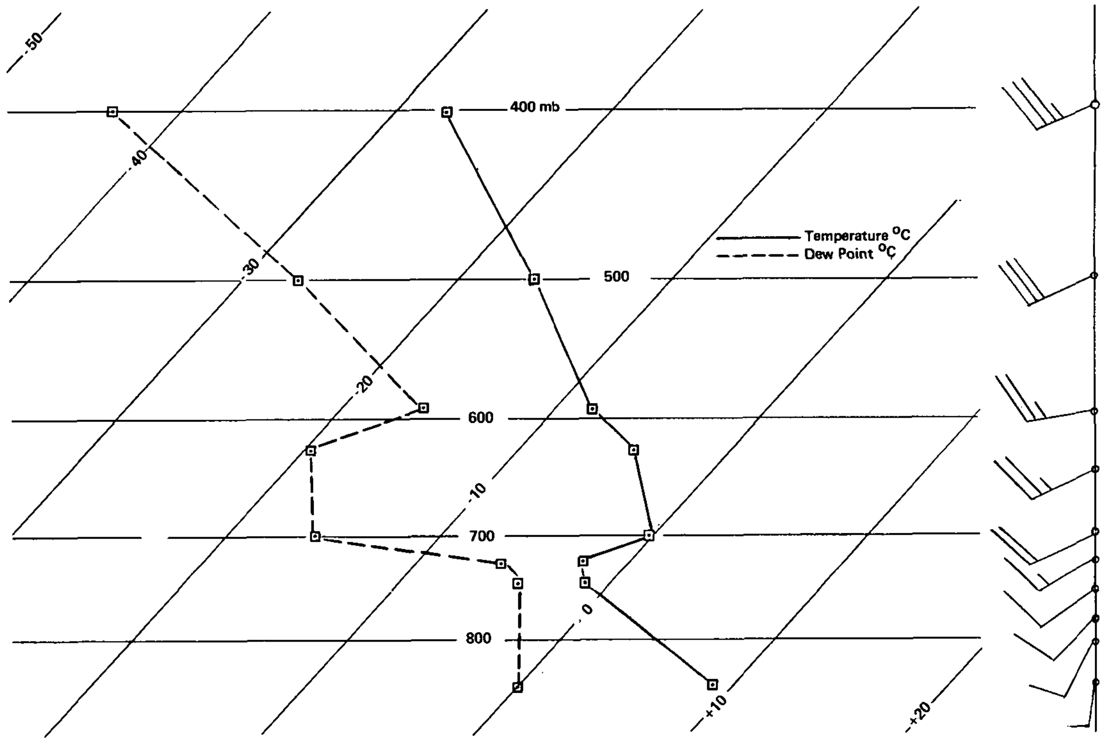

FIGURE 2.—Winnemucca, Nev., radiosonde ascent for 0000 GMT (1600 PST), Dec. 5, 1970.

TABLE 1.—*Richardson numbers* (Ri) *computed from the Winnemucca, Nev., radiosonde flight for 0000* GMT, *Dec. 5, 1970*

Layer	Dry process	Cloudy process
Intermediate	2.0	−0.1
Inversion	6.4	0.2

present and can easily be observed at the top of a haze or smog layer over a city. These waves do not significantly enhance the transport mechanism across the layer. Effective transport across an inversion will only occur, therefore, at those places where waves are breaking. It is not without significance that the evaporation processes of individual drops may be quite different under these circumstances than otherwise. This could, for example, lead to larger drops traveling with the crest of the breaking wave falling into the trapped clear air beneath it, where there is time for the drop to evaporate and rapidly approach its wet bulb temperature. If the air temperature should be sufficiently low (say −10°C), this could lead to nucleation at the lower temperature with the possibility of the drop freezing under nonequilibrium conditions (Johnson and Hallett 1968) with shattering and the production of numerous satellite ice crystals. This was not observed in the present situation—the temperature was probably too high (−3°C). It is tempting to speculate that the observed wide variability in the occurrence of ice crystals in layer clouds may thus be linked with the fortuitous occurrence of breaking waves at the layer top.

Our knowledge of wave instability in the atmosphere comes from high powered radar techniques, the use of aircraft capable of high resolution measurement, or careful observation of an inversion layer from a site at about the same level. Such techniques can hardly be used on a routine basis for assessing the frequency of occurrence of breaking waves. Further studies must therefore aim at examining those situations in the atmosphere when vertical transport and ice nucleation processes would be especially sensitive to the occurrence of breaking waves.

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